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Carl A. Sandahl and James L. Raper [1964] 13p refs

NASA Langley Research Center,
Langley Station, ~~Hampton~~, Va.

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CURRENT STATUS OF THE SOLID-PROPELLANT FLIGHT-TEST VEHICLE

Carl A. Sandahl* and James L. Raper*
NASA Langley Research Center
Langley Station, Hampton, Va.

The capabilities and limitations of the staged, solid-propellant rocket vehicle system for conducting aerodynamic tests within the atmosphere are discussed. Problem areas in aerodynamics, dynamics, propulsion, and trajectory control peculiar to these systems are covered. Some cost data are included. AUTHOR

Introduction

Today's talk is directed at the project manager who is faced with the task of securing aerodynamic test data for a configuration or purpose for which ground facilities prove to be inadequate. We will discuss how the solid-propellant flight-test vehicle can be used in such situations, what are some of its operational problems, and what are the costs.

The use of solid-propellant flight-test vehicles for aerodynamic testing has advanced from single-stage systems capable of subsonic speeds 20 years ago to complex multiple-stage vehicles capable of near-orbital speeds today. Numerous vehicle configurations have been developed over the years to meet various payload requirements. Generally, the new configurations have taken advantage of the new rocket motors and advancing state of the art. With practically each new vehicle system some new problem area has been uncovered and subsequently solved. Today we plan to touch briefly on general problems which have plagued these vehicle developments and to elaborate on those special problem areas which have resulted from the more advanced vehicle systems now being employed to boost larger payloads to higher velocities.

In order to place some practical bound on our discussion, only operational or near operational, unguided, aerodynamically stabilized vehicles operating within the atmosphere will be considered. These vehicles spread over a range which includes the $1,200 one-stage Arcas meteorological rocket with a payload weight of approximately 10 pounds up to the $400,000 $M = 24$ three-stage RAM B vehicle with a payload weight of approximately 200 pounds. In between are multistage systems capable of a range of payloads and velocities.

Fig. 1 shows one of the current multistage vehicles capable of $M = 20$ with various payload sizes.

Within the aforementioned bounds, let us examine the capability of the unguided solid-propellant rocket vehicle as it exists today for performing aerodynamic testing.

A bibliography of vehicle technology is included at the end of the paper.

Attainable Test Spectrum

For the systems under discussion, the attainable test spectrum is governed primarily by rocket motor staging, payload weight, and drag. However, certain other considerations have an influence.

Fig. 2 shows in general the aerodynamic test corridor covered by present and projected vehicle systems. The effort and cost required to conduct a flight test increases with speed and the offset from the center line of the corridor.

The corridor is bounded on the upper side by considerations of aerodynamic stabilizing forces (weather cocking) which are required to aline the vehicle with the flight path on a near nonlifting ballistic trajectory. Remember that these are unguided vehicles. The lower corridor boundary is determined by aerodynamic loading considerations and the capability of a structure to withstand these loads. The maximum velocity is, of course, governed largely by the total impulse of the system. Maximum velocity also appears to be limited by increasingly unfavorable thrust-to-drag ratios on the final stages of these all-atmospheric vehicles. Dispersion also begins to appear as a secondary limiting factor for near orbital test speeds.

A nonlimiting factor, but one of increasing importance as velocity is increased, is telemetry signal attenuation. This problem is aggravated by increased body bluntness, low signal strength and frequency, and lowered antenna efficiency. Alleviating factors for this problem are suggested by the aforementioned factors. Other means of circumventing the problem include materials injection and data storage and playback.

With a general test corridor, so defined, let us now examine some of the special problems attendant to the successful operation of vehicles capable of operating within this corridor.

Aerodynamics

Aerodynamically speaking, the rocket vehicle systems we are talking about are quite sophisticated flying machines. As noted earlier, they are capable of flight within the atmosphere at near orbital speeds. Indeed this is the capability which renders them attractive for certain test purposes, but at the same time requires advanced aerodynamic design considerations.

The aerodynamic design of a rocket vehicle system includes the conventional textbook prediction of the force and moment derivative for all three axes. These methods have been developed and are well documented. One note of caution is in order however. The interference effects of tandem lifting surfaces have got to be carefully accounted for particularly in the case of the rolling derivatives. Current analytic methods will work, but they must be used with care and diligence.

*Aerospace Engineer, Vehicle Performance Branch, Applied Materials and Physics Division.

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So much for the more classic aerodynamic problems. In Fig. 3 are shown some of the current more special problem areas. At the low-speed end of the chart is shown an area called large angle-of-attack forces. This covers the low-speed part of the flight starting with lift-off during which time the vehicle attitude is sensitive to winds. Quite satisfactory wind weighting methods for correcting launcher angles have been devised; however, they generally require force and moment data up to and beyond 90° angle of attack. The requirement for accurate large angle-of-attack force data increases as the lift-off acceleration decreases. In some cases wind-tunnel tests at these large angles of attack have been required. To further complicate this picture it appears that the so-called quick spin vehicles may require consideration of the effects of spin on the forces and moments during lift-off.

The next special problem area is shown on the chart at about $M = 1.0$ and is denoted by venting. The venting problem is generally not handled sufficiently well and frequently is considered only as an afterthought. The venting problem is caused by airflow within and through the vehicle occasioned by changes in the atmospheric pressure and in the pressure distribution around the vehicle. Usually the pressures and/or pressure distributions change slowly enough so that the leakage flow prevents any large buildup of pressure sufficient to cause structural failure. For example, the changes in pressure due to change in altitude alone are not generally a problem. However, the changes in pressure distribution which occur in accelerating through the transonic speed range can lead to large, momentary pressure imbalances which can fail improperly designed elements. Heat shields for example are susceptible to failure in this mode. The venting problem can be handled with proper attention to design detail. Detailed transonic wind-tunnel pressure-distribution tests have been called for on occasion.

The next problem area is that concerned with heating and heat protection. The heating problem is indeed a severe one. However, the problem is alleviated to some extent by the fact that the exposure times are generally relatively short. Heat sink and ablative protection methods are generally adequate. The main problem is to have proven methods for predicting temperatures and ablative material requirements.

The remaining special problem area is that of the jet plume. As the attitude increases the pressure of the exhaust jet relative to the ambient pressure increases resulting in a large, and for aerodynamic considerations, a relatively solid jet plume. This plume separates the flow over the vehicle to an extent sufficient to render the stabilizing surfaces ineffective over a fairly substantial angle-of-attack range during powered flight. Lowering the rocket chamber pressure and increasing the nozzle expansion ratio have small beneficial effects. The size of the plume is mainly governed by the ambient pressure and is therefore mainly governed by the pressure attitude.

There appears to be no generally acceptable passive way of combating the instability problem caused by the jet plume. The main solution appears to be to live with the problem and to make proper allowances. For example, the instability is limited to a finite angle-of-attack range. Therefore the vehicle motion during the time of influence of jet pluming is essentially a bounded coning oscillation and the mean flight path is essentially that for zero lift flight. As the motor thrust tails off the motion will tend to diminish depending on vehicle damping and stability. The angle of attack will approach a sufficiently small value so that aerodynamic tests can be made or a subsequent stage can be fired without introducing unacceptably large dispersion. More will be said on this later.

These then are some of the current special aerodynamic problems areas. The areas shown are navigable, but require particular attention.

Dynamics

The primary dynamics problem for the unguided rocket vehicle is the classical one of avoiding frequency coupling and resonance. The frequencies of concern are the structural bending (usually the first mode), the short period longitudinal pitching and/or yawing frequency, and the vehicle spin rate. These are illustrated in Fig. 5. Seldom if ever do the structural and the aero short-period frequencies resonate. Unfortunately, this cannot be said for the spin frequency. Basically the problem becomes one of arranging the spin program so that the spin rate is never allowed to dwell at either of the other frequencies. Numerous ploys are available for accomplishing this.

First however we should examine why the vehicles are spun, since this is the cause of the problem. There are two reasons: First, it is impossible to prevent some small amount of spin resulting from manufacturing tolerances. Second, spin is used to minimize trajectory dispersions which would result from effects of thrust misalinement and stage separation tip-off. Admitting then the desirability of spin, we might look at two current methods of producing the spin program. The first is simply to cant the fins on the several stages in some clever way in order to produce the desired spin program. This does work; however, there are cases where the spin so generated plus the accidental spin could approach the aero short-period frequency. The second method is to use spin motors for adjusting the spin rate at appropriate times during the flight; usually, immediately at lift-off as shown in the figure. Either of the methods or combinations thereof are used successfully.

The foregoing are dynamics problems peculiar to the class of vehicles under discussion. In their design the classical problems of flutter and aeroelasticity must, of course, also be considered.

Propulsion Considerations

The most important element of the vehicle systems we are talking about is the solid-propellant rocket. The rocket has an interplay with the rest of the system which introduces considerations other than simply their thrust producing capability. Some of these interplaying factors are shown in Fig. 4. Burn time has been chosen as the independent variable. Stage total impulse is assumed constant. Increasing burn time for purposes of this chart implies a trend from quick burning, high pressure, high thrust, metal case motors towards lower pressure, lower thrust, high mass fraction, glass wound motors having somewhat poorer structural capabilities when considered as structural elements in a staged vehicle system.

Some of this interplay is shown on this figure. Favorable trends are shown dashed. The propulsive efficiency increases with increased burn time reflecting increased propellant performance and improved mass fraction obtained with the lower pressure glass wound motors. The increasing burn time and lower pressure leads to only a relatively small reduction in jet plume. A favorable reducing trend of the longitudinal loading is also obtained. This may be of importance to the survival of the electronics systems.

These three aforementioned trends are favorable to some degree. However, the lower two trends on the chart, performance predictability and structural efficiency, are unfavorable and are frequently governing. The performance predictability is lowered because the drag, which is usually an estimated value subject to fair sized errors, has a longer time to act. Furthermore there is a compounding effect. For example, suppose the drag coefficient levels are higher than predicted. Then the drag force levels will be higher for two reasons; namely, the initial error in the coefficient plus the fact that the trajectory will necessarily be lower than expected leading to higher dynamic pressures and further increases in drag force. It is in this important respect that the performance of these all-atmospheric flight vehicles differs from vertical or near vertically launched probes and missiles.

The remaining trend we note is the reduced structural efficiency. This is not to imply that the rockets themselves are structurally inefficient. It is when they are incorporated in a vehicle stack and they must serve as elements of a slender, transversely loaded elastic beam that they show a reduction in structural efficiency. On occasion these high-performance motors have required additional load-carrying structure which negates part of their efficiency.

These then are the more important rocket considerations.

Trajectory Problems

Perhaps the best way to discuss trajectory problems is to follow through a typical flight as shown in Fig. 6.

Immediately at lift-off the largest forces acting on the vehicle are the thrust and weight. Aerodynamic stabilizing forces are negligible. Consequently thrust misalinement is the predominating perturber of the flight path. Quick spin methods solves this problem. The quick spin is produced by small quick burning spin rockets.

Also acting at this time and for some additional period of time are the perturbing forces of the wind. Using detailed wind observations prior to a flight test, acceptable methods for wind weighting (launcher angle settings) have been devised for compensating for most of the wind effects. These methods involve precomputing wind sensitivity curves showing the launcher adjustments required. In addition, increasing vehicle acceleration at lift-off shortens the time the winds are most detrimental. The assisted lift-off is accomplished by strapping auxiliary propulsive rockets to the first-stage booster.

Following first-stage burnout, of course, is the ignition of the subsequent stages. Generally this is done with preprogramed timers. However, for some cases where the accumulated trajectory errors during first stage may be excessive, a command firing system for igniting the subsequent stages has been used. With this system the stages are ignited by radio command later or earlier than the nominal in order to attain the required payload test region. This system, of course, includes a real-time read out of pertinent trajectory parameters, their interpretation and decision making schedules.

Stage separation generally implies some disturbance to the flight path. The problem is to choose the simplest separation system which will give sufficiently small disturbances. The separation systems vary from the relatively simple hot blow-off systems, the explosive shaped charge, to the more complicated cold separation system. Spin, of course, generally minimizes the net trajectory change.

As the altitude increases the deleterious effects of jet pluming previously noted become significant. The plume causes a bounded vehicle attitude oscillation during powered flight. This oscillation must be damped to acceptably low limits for test purposes or prior to ignition of subsequent stages. The only useful design tool for predicting the magnitude of this problem now is a complete six-degree-of-freedom machine computer program. Particular attention is paid to the jet damping derivatives and the nonlinear static stability of the vehicle in the presence of the plume. Computer studies of this type define the range of oscillation and/or dwell times required for damping prior to subsequent stage ignition.

As the flight proceeds we become concerned with the ability of the vehicle to go "over the top," that is, its ability to weathercock along the flight path. Again the computer is used to advantage, particularly for the spinning vehicle.

The remainder of the trajectory problem is that of predicting dispersion. We are concerned with the dispersion of the payload from its desired aerodynamic environment, that is, the desired box in the sky, as well as the impact dispersion of the various stages for range safety consideration. Dispersion calculation are, in large measure, judgment techniques justified by statistically oriented trajectory computations. The problem becomes of more concern as orbital speeds are approached.

Trajectory considerations indicate that the best overall staging arrangement appears to be as follows: For the relatively low thrust-to-weight first-stage long-burning motors with assisted lift-off are desirable to "lob" the subsequent stages and payload through the lower altitude range. Moderate to high fast burning thrust-weight ratio motors are desirable for the subsequent stages.

Cost

Assuming that the development costs have been largely amortized and that the payload costs are excluded, the rocket motors are generally the largest single cost item in a vehicle system. In order to arrive at some very general cost factors suitable for estimating purposes, data for numerous current and projected systems were accumulated and are shown in Fig. 7. Shown here is the vehicle cost per pound of payload plotted as a function of the maximum velocity. This is representative of the cost of a complete system, assembled and erected on the launcher ready for firing. Excluded are development costs and payload costs.

As might be expected, the results show a rapid increase in cost as speed and/or payload weights increase. The uninitiated might be surprised at the level of the cost factor itself. This kind of testing does not come cheaply; for example, consider a moderately ambitious proposal to test a 200-pound payload at a Mach number of 20. The total vehicle cost comes out to be $200,000, a substantial amount indeed.

Concluding Remarks

Some of the capabilities, limitations, and costs staged solid-propellant unguided vehicles for conducting tests within the atmosphere have been discussed. These vehicles are capable of producing a wide variety of aerodynamic environments, a number of which are unattainable in ground facilities. The technology for these vehicle systems has been well developed, but needs broader and deeper application in the development of current and new systems.

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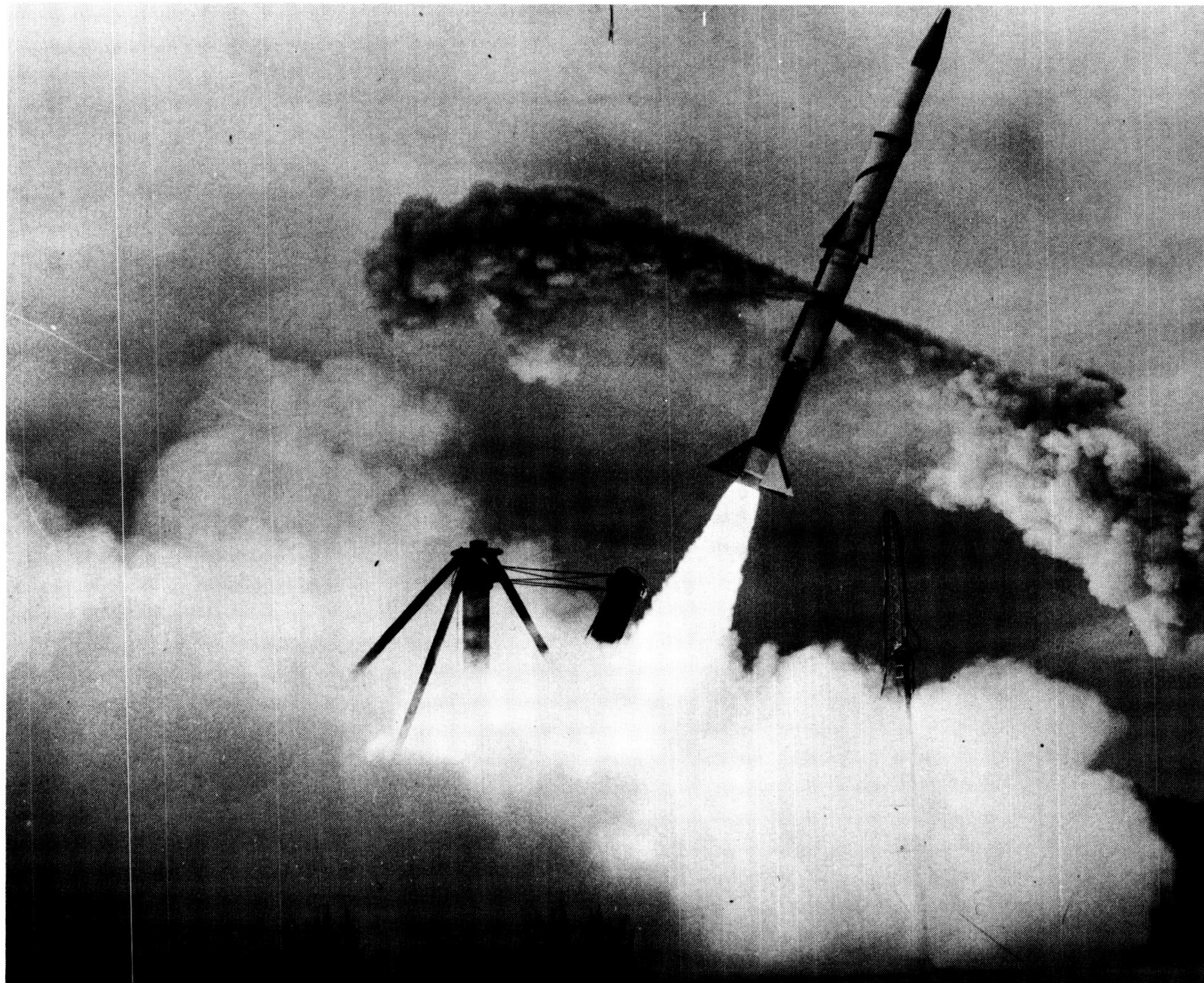

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Figure 1.- Multistage vehicle launch.

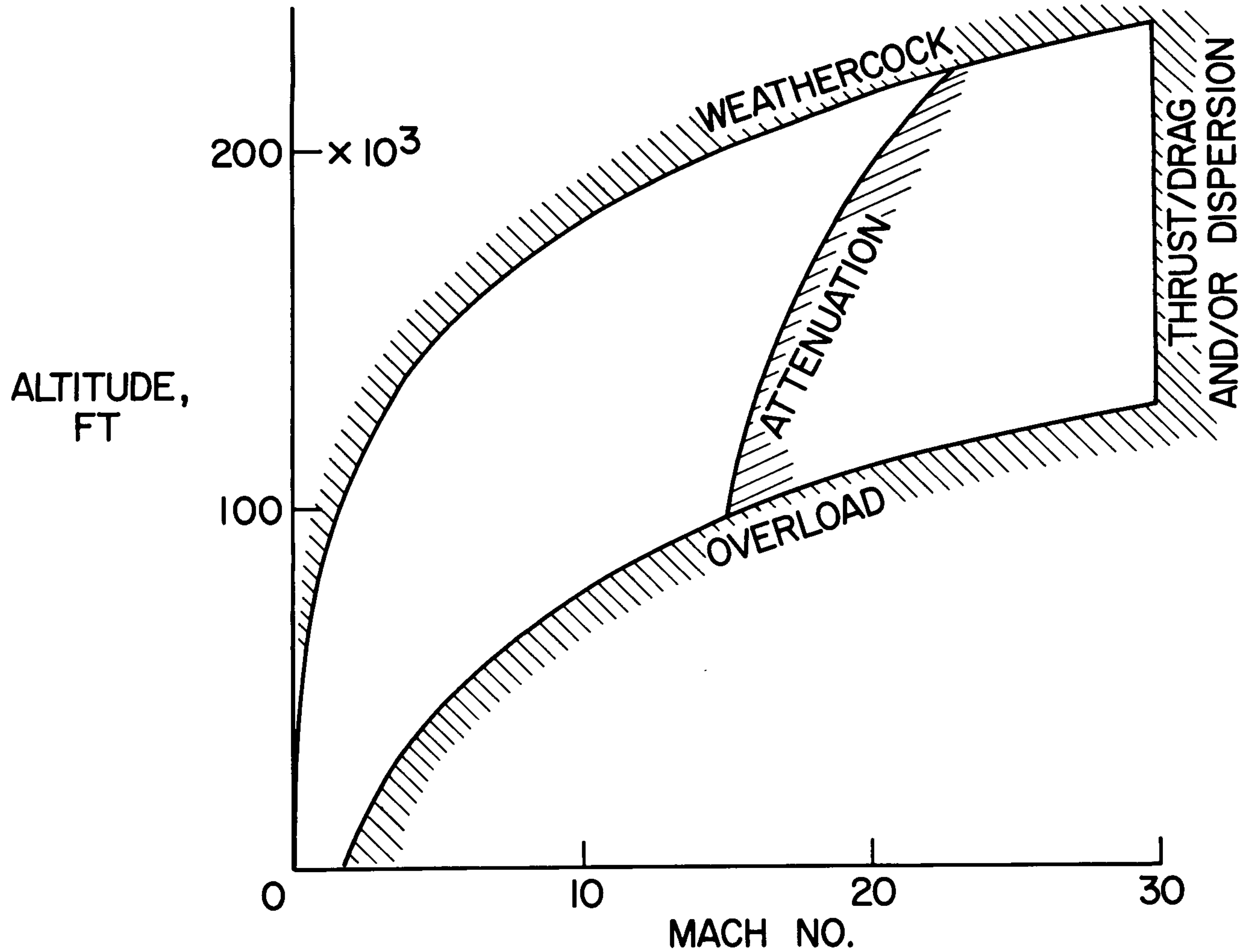

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Figure 2.- Test spectrum.

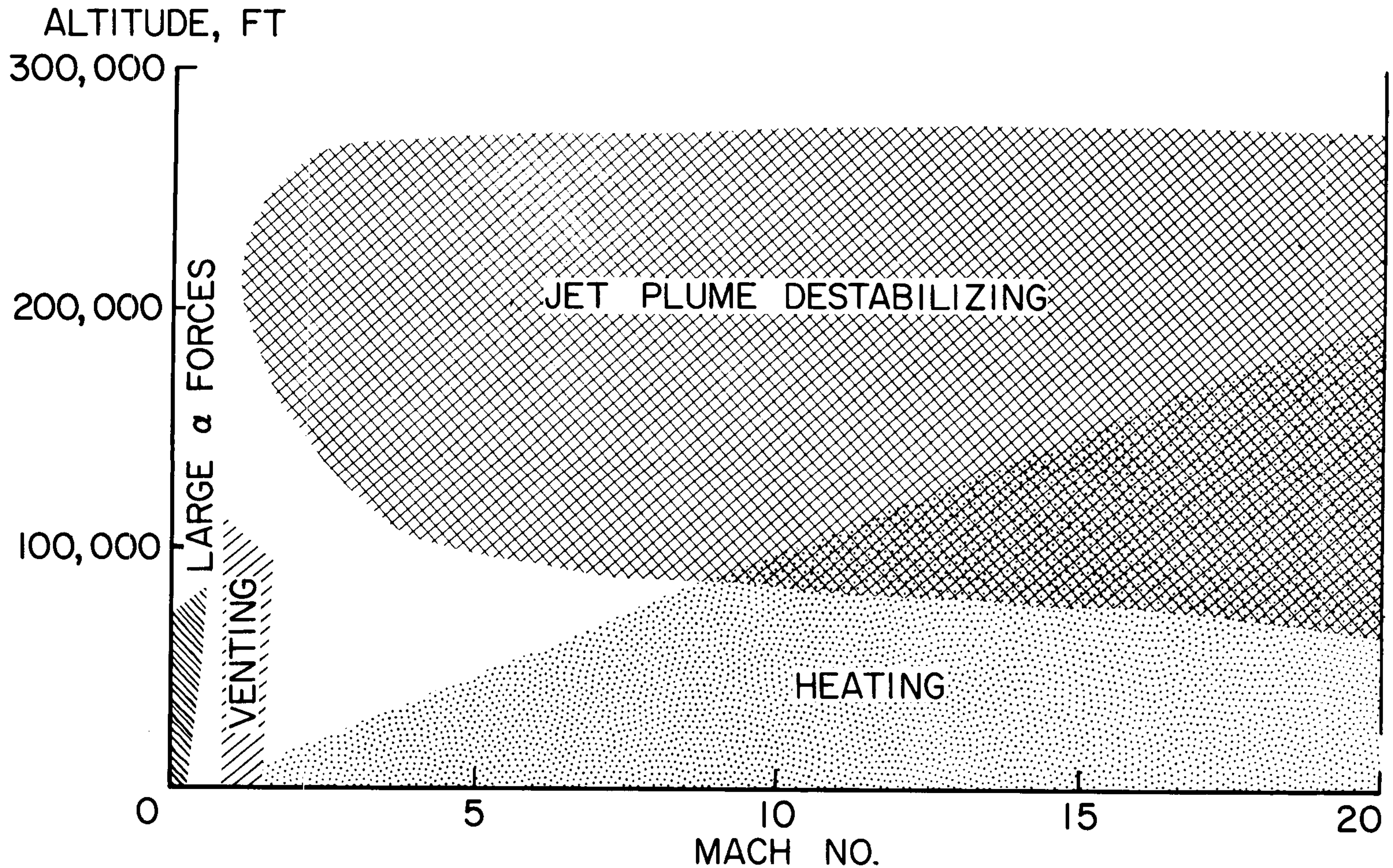

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Figure 3.- Aerodynamic problem areas.

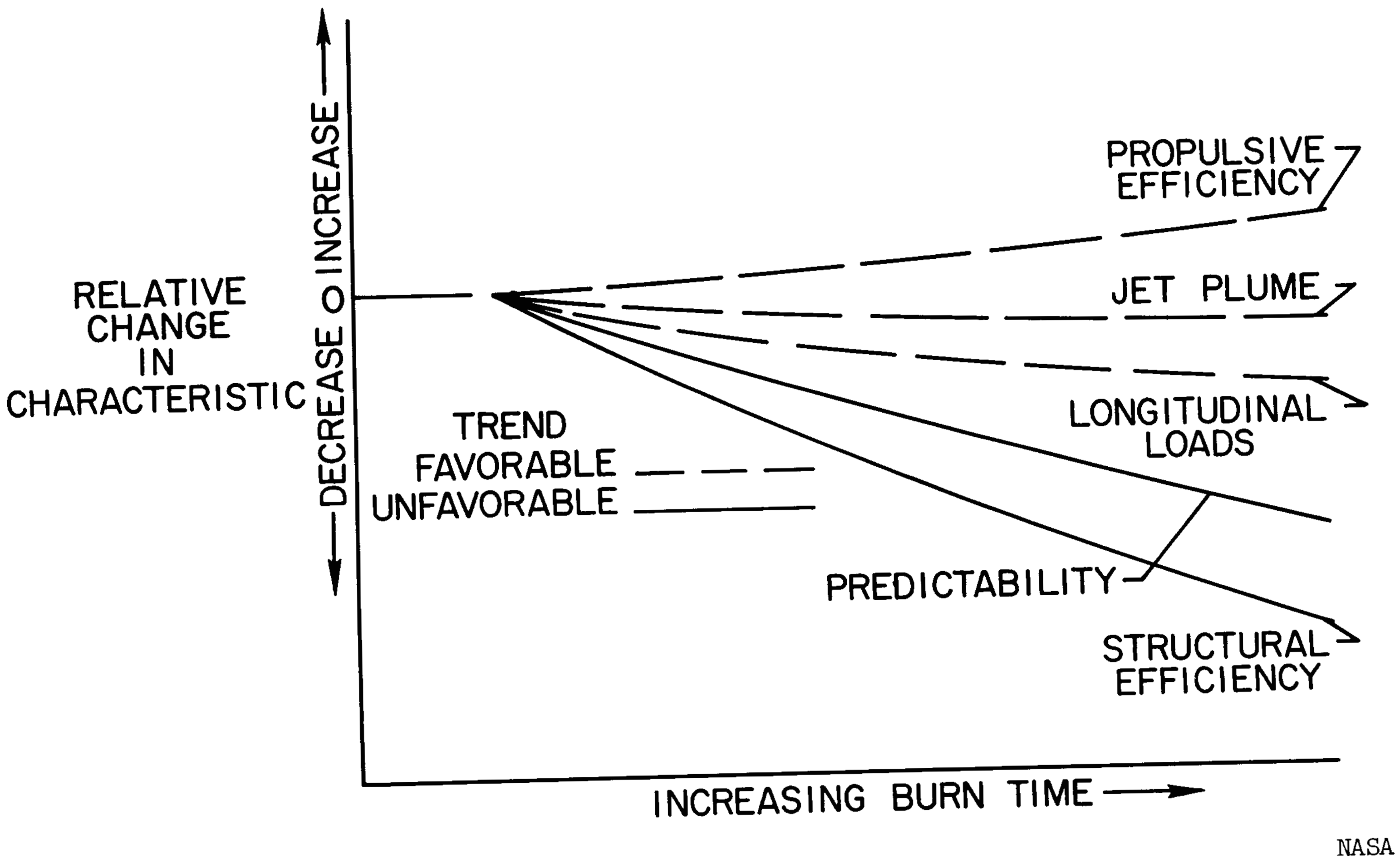

Figure 4.- Propulsion considerations.

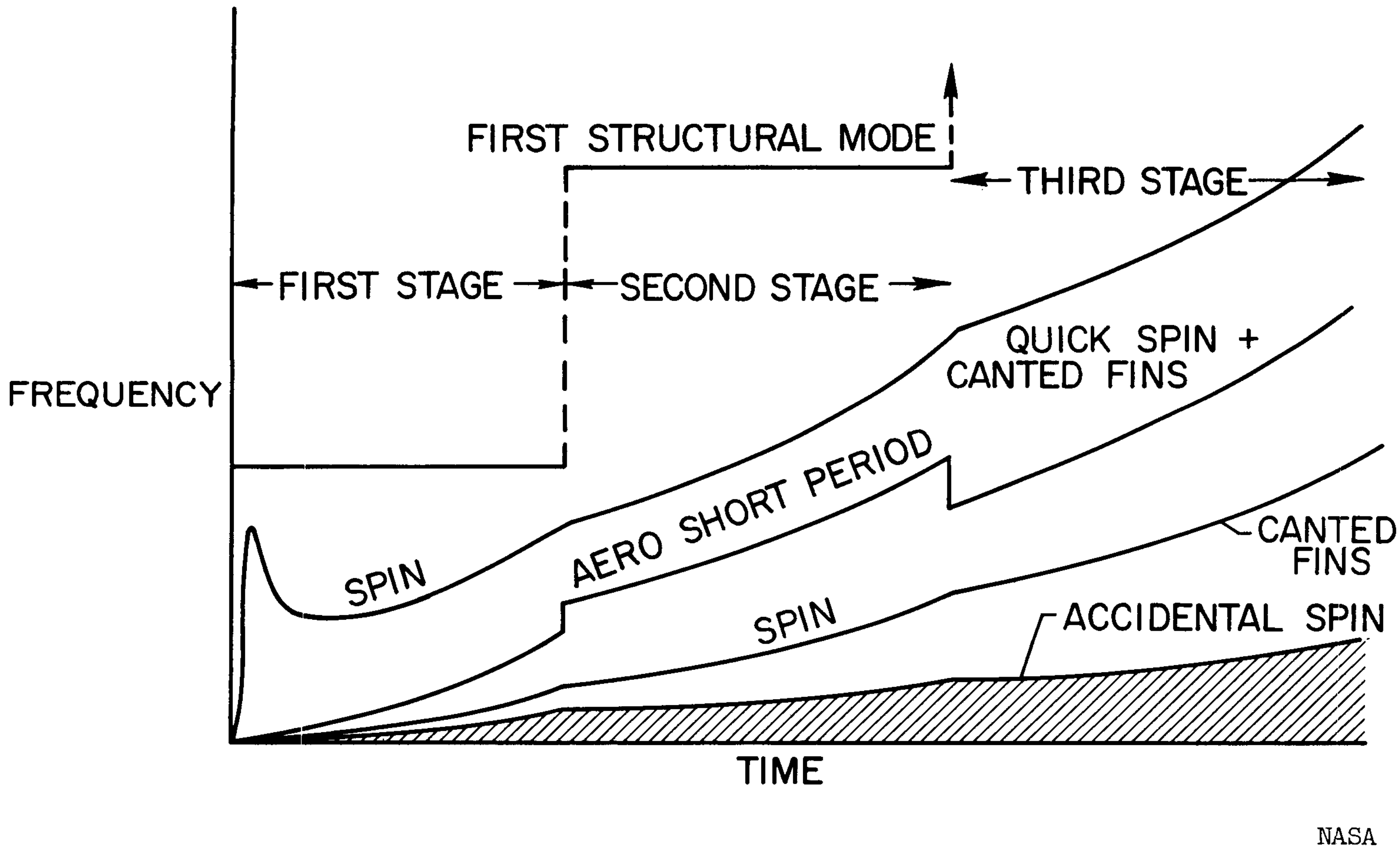

Figure 5.- Dynamics problem areas.

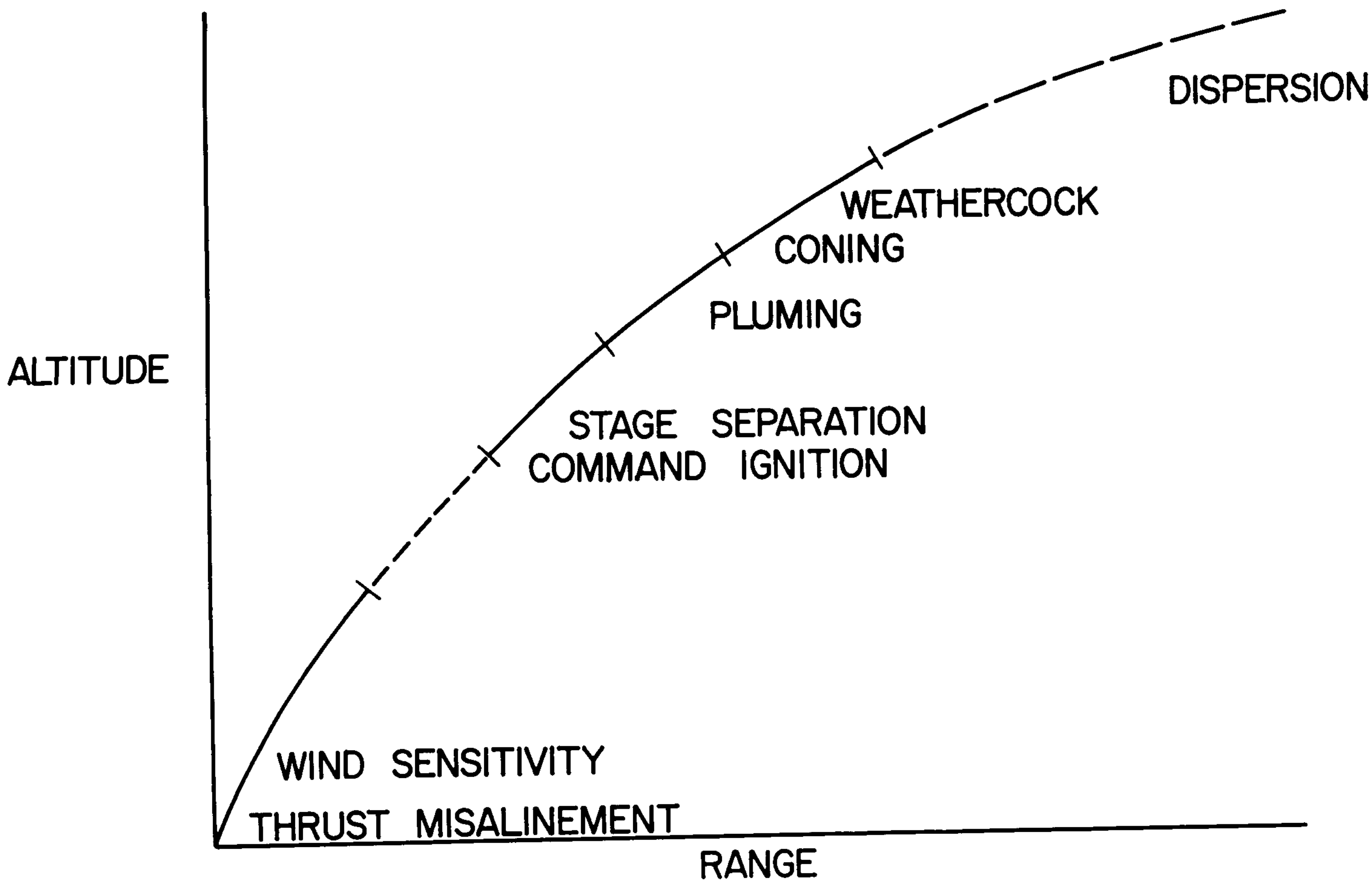

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Figure 6.- Trajectory problem areas.

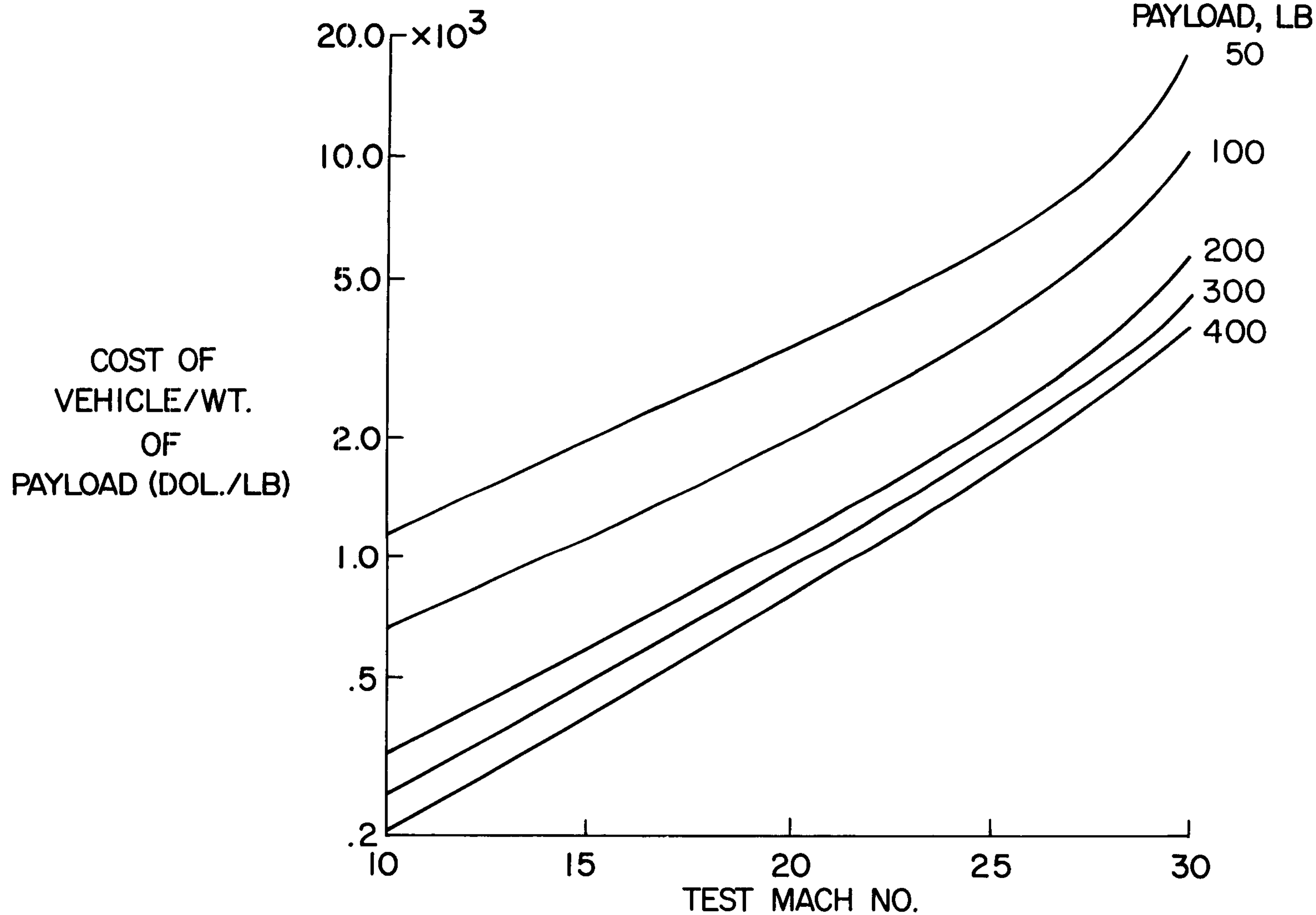

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Figure 7.- Vehicle cost.

NASA-Langley, 1964